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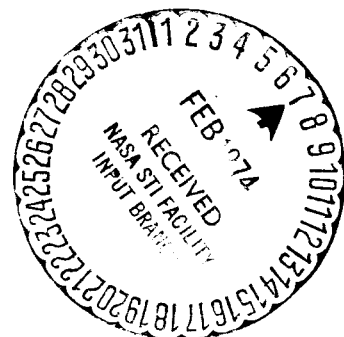
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MINIMUM LIFT-TO-DRAG RATIO REQUIREMENT FOR THE LUNAR MISSION

By Jon C. Harpold
Mission Analysis Branch



MISSION PLANNING AND ANALYSIS DIVISION



MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO


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MINIMUM LIFT-TO-DRAG RATIO REQUIREMENT

FOR THE LUNAR MISSION

By Jon C. Harpold

SUMMARY

This internal note presents the results of a study to determine the minimum required lift-to-drag ratio (L/D) for the Apollo command module (CM) for the lunar missions. The results indicate that the minimum L/D requirement for the lunar mission is 0.25. This L/D will allow the following operational flexibility without causing an excessive performance penalty due to reballasting of the CM.

1. It will allow a 1000-n. mi. reentry maneuver capability if the Manned Space Flight Network (MSFN) is available and the guidance and navigation system (G&N) is working.

2. It will provide capture for all cases where MSFN is available and the maneuvers are executed with the stabilization and control subsystem (SCS).

3. It will allow capture and a minimum maneuver capability of 500 n. mi. with a 3σ steep flight-path angle, if the MSFN is not available but the service module reaction control system (RCS) is available for midcourse corrections.

4. It will insure capture if the transearth maneuver is retargeted for the case where the MSFN is not available and the RCS is inoperative.

INTRODUCTION

Because of the large increase in the weight of the unballasted CM, the L/D has been decreased to less than 0.30. In an effort to avoid ballasting the CM to maintain a minimum L/D of 0.30, a study was conducted to define the minimum required L/D for the lunar mission. If it could be verified that the minimum required L/D was significantly less than 0.30, additional ballast would not have to be added to the CM. The current L/D specifications (ref. 1) state that the minimum L/D will be at least 0.30 at a speed of 25 000 fps, and the L/D limits for subsystem design vary from 0.30 to 0.40. The specifications also state that the command module must be able to land at a recovery point between 1500 and 2500 n. mi. down range from the entry point for lunar

missions. In addition, the L/D must be large enough to ensure capture for the largest expected deviations in the entry corridor. To ensure this, the reentry corridor requirement is 20 n. mi., which is approximately equal to a 1.5° flight-path angle corridor. In order to re-evaluate the minimum lift-to-drag requirement, it was necessary to examine all the factors that relate to the requirement for L/D.

The minimum L/D requirement is dependent upon the subsystem design limits, the reentry range requirement, the maneuver capability requirement, and the reentry corridor depth requirement. The purpose of this internal note is to discuss each of the factors relating to the requirement for L/D and to recommend a minimum L/D for the lunar mission.

SUBSYSTEM DESIGN LIMITS

The first factor affecting L/D is the subsystem design limit. The four CM subsystems that depend on the L/D are the G&N system, the entry monitoring system (EMS), the CM control system, and the thermal protection system. The L/D requirement for the thermal protection system has been investigated and will be documented by the Structures and Mechanics Division (SMD). Therefore, the thermal protection system will not be discussed in this document, except to mention that the thermal limitations do not appear to be a strong function of L/D and thus, do not affect the lower limit of L/D.

Guidance and Navigation System

The current G&N system was designed to operate with an L/D of between 0.30 and 0.40. An evaluation of the current G&N guidance logic for an L/D range of 0.20 to 0.30 was performed, and the analysis showed that the current guidance system will not operate satisfactorily for this L/D range. Within this low L/D range, the current guidance system caused the CM to miss the target area by as much as 500 n. mi. with an average miss distance of approximately 100 n. mi.

The Massachusetts Institute of Technology (MIT) and the Mission Planning and Analysis Division (MPAD) have determined the basic revisions to the guidance logic in order to make it perform satisfactorily for an L/D as low as 0.20. This analysis is documented in references 2 and 3. These modifications include changes in several guidance constants and a revision to part of the iteration logic in the guidance equations. These changes also produce a requirement for additional entry parameters to be placed in the erasable memory of the Apollo guidance computer (AGC). Table I lists these changes and the purpose for each change. With this updated guidance logic, adequate performance was demonstrated throughout most of the entry corridor. However; it should be noted that several minor problems still exist in

this new logic. Work is continuing in this area to minimize these problems.

No major schedule slippage for the guidance program is anticipated as a result of reducing the L/D. However, it should also be pointed out that as the L/D decreases, the acceptable uncertainty in L/D is decreased without a resulting guidance performance degradation. For example, with a nominal L/D of 0.25, the guidance accuracy degrades as the uncertainty in L/D exceeds ± 0.05 units.

Entry Monitoring System

The entry monitoring system was also designed to operate between an L/D range of 0.30 to 0.40. North American Aviation (NAA) has stated that if the L/D drops below 0.30, the EMS monitoring scroll would have to be redesigned. It is estimated that it would take from 6 to 9 months to develop and deliver an updated monitoring scroll. On this monitoring scroll, modifications would have to be made to the skip-limit lines, the maximum load factor limit lines, and the entry ranging lines. Besides the monitoring scroll changes, the resolution factor used in the velocity calculation would have to be changed. This is a minor hardware change as long as the L/D remains at least 0.20.

It should be noted that a G&N-EMS compatibility problem may exist (as currently exists for the high L/D patterns), and this will not be definitely known until the guidance logic is finalized and additional work is done on EMS scroll design. If this incompatibility does exist, further modifications may be necessary with the resultant further slippage in the delivery of an acceptable EMS monitoring scroll.

Command Module Control System

The command module computer (CMC) sends commands to the CM control system by means of the digital autopilot (DAP). This system is currently designed to normally operate with either one or two RCS rings and with a maximum roll rate of 20 deg/sec. With a reduction of the CM L/D to below 0.30, it may be necessary to raise the maximum roll rate in the DAP or to normally operate with two RCS rings during the first entry phase of the lunar return entry. Further study needs to be done in order to determine the feasibility and need for the above changes.

REENTRY RANGE AND MANEUVER CAPABILITY REQUIREMENT

The next factor affecting the minimum L/D requirement is the reentry range and maneuver capability requirement. Sufficient maneuver capability must exist in order for the G&N system to compensate for transearth trajectory dispersions and entry dispersions. Maneuver capability is also needed to avoid bad weather which might enter the recovery zone after the transearth injection maneuver of the lunar mission. At the current time, it is felt that a 1000-n. mi. maneuver capability during the entry phase is needed to accomplish the above tasks. The minimum guided range on the overshoot boundary is 1500 n. mi. Therefore, in order to satisfy the 1000-n. mi. capability requirement, the G&N system must be able to achieve accurate touchdown control between the entry ranges of 1500 and 2500 n. mi.

Figure 1 shows the L/D requirement as a function of maneuver capability. A change in the maneuver capability of 100 n. mi. changes the L/D requirement by 0.005.

ENTRY CORRIDOR REQUIREMENT

The reentry corridor depth requirement is a direct function of the accuracy of the transearth midcourse correction (TEMC). Table II lists the TEMC accuracy that can be expected as a function of the spacecraft attitude control mode for the maneuver, the propulsion source, and the method of navigating for the transearth injection and midcourse corrections. The spacecraft attitude can be controlled by either the primary G&N system or the SCS. The propulsion source can be either the service propulsion system (SPS) or a combination of the RCS and SPS system. If RCS is available, the large maneuvers will be made with the SPS, and the small maneuvers with the RCS. Navigation data may be obtained from the MSFN or the CM optics. This table shows that the TEMC maneuvers using a combination of SPS and RCS thrusting are far more accurate than the TEMC maneuvers using just the SPS thrusting system.

To translate these TEMC accuracies into corridor and L/D requirements, the entry corridor definition and entry targeting procedure must be examined. The entry corridor, as shown in figure 2, consists of four primary control lines. These are the negative-lift overshoot, the zero-lift overshoot, the 2500-n. mi. range limit undershoot, and the 10g full-lift undershoot boundaries. With an operating G&N system during the reentry, a successful reentry can be flown between the negative-lift overshoot and the 2500-n. mi. undershoot boundaries. The 2500-n. mi. undershoot boundary is used because below this boundary a 1000-n. mi. maneuver capability does not exist.

Without an operating G&N system, a reentry can be successfully flown only between the zero-lift overshoot and the 10g undershoot boundaries. The zero-lift boundary was selected for the overshoot limit because manual control to ensure a safe entry is extremely critical between the zero-lift overshoot and the negative-lift overshoot boundaries. Manual control could easily result in either excessive load factor levels or skip out during reentry. Therefore, for targeting purposes the zero-lift overshoot should be used as the overshoot boundary. The 10g undershoot boundary was chosen as this is a crew constraint level and allows a wider corridor allowance for a given value of L/D. It was not considered necessary to provide a 2500-n. mi. range capability, because it is doubtful that a long range trajectory would be attempted without a functioning G&N system.

To protect against a G&N failure prior to entry, the reentry target flight-path angle must be placed below the zero-lift overshoot boundary by the 3σ flight-path angle dispersion. This will enable the CM to always be in the acceptable open-loop corridor. Therefore, the minimum L/D is determined by the requirement to have a sufficiently wide corridor between the zero-lift overshoot boundary and the 2500-n. mi. undershoot boundary. The corridor width is determined by the TEMC accuracy.

The minimum L/D requirement is a function of how the transearth maneuver is targeted and the failure cases that are to be actually considered. The targeting criteria can be divided into two areas. These are (1) the distance away from the overshoot boundary to ensure capture and (2) the distance away from the undershoot boundary to meet the ranging requirement. The target line is placed with respect to the overshoot boundary at the largest flight-path angle dispersion that is theoretically possible for the TEMC navigation and control mode considered. For example, using the data from table II, if neither the MSFN nor the RCS were available, the target line would be placed 1.0° below the zero-lift overshoot boundary. If the MSFN were not available but the RCS was available for small maneuvers, the target line would be 0.57° below the zero-lift overshoot boundary. If the MSFN were available, but there was no RCS for maneuvers, the target line would only be 0.50° below the zero-lift overshoot boundary. The 0.50° dispersion corresponds to an SCS attitude control mode, which was used rather than the dispersion associated with the G&N attitude control mode. This ensures capture if the G&N failed prior to executing all midcourse corrections.

The corridor requirement between the target line and the undershoot boundary is determined by how many actual failure cases are to be considered while still maintaining the 1000-n. mi. reentry maneuver capability. If no failures are to be considered, only 0.03° need be

allowed between the target line and the 2500-n. mi. undershoot boundary. If the RCS is inoperative, 0.38° is required. If the MSFN is not available, 0.57° is required; and if neither the MSFN nor the RCS are available, a 1.0° corridor is required between the target line and the 2500-n. mi. undershoot boundary.

By combining the above corridor depth requirements and using figure 3, a minimum L/D requirement can be determined. Figure 3 shows the minimum L/D requirement as a function of total corridor depth needed between the zero-lift overshoot and the 2500-n. mi. undershoot boundaries. Table III gives a summary of all of the above cases and the L/D requirement for each case. Based on the data in table III, it is felt that the absolute minimum L/D must be at least 0.25. This L/D would allow for the operational flexibility needed for the lunar mission. It is further recommended that the MSFN be considered unavailable for establishing the targeting criteria. This would allow a 1000-n. mi. maneuver capability for all failure cases except when the MSFN is unavailable or both the MSFN and the RCS are unavailable. If the MSFN is not available approximately a 500-n. mi. maneuver capability would exist at the 3σ steep flight-path angle. If both the MSFN and the RCS are unavailable, the transearth maneuver would have to be retargeted in order to guarantee capture. No maneuver capability would be available at the 3σ steep flight-path angle and approximately a $13g$ to $14g$ reentry would be experienced.

The transearth trajectory data was generated by the Maneuver Analysis Section of the Mission Analysis Branch. Table II lists the conditions and failures that were used in each case. It should be noted that in all of the onboard cases (cases 3 and 4), a 1σ sextant accuracy (20 arc seconds) was used. Also, a star-landmark technique was used instead of the star-horizon technique. The accuracy on the landmarks was assumed to be ± 1 n. mi. This means that the data used in this study is probably optimistic for the cases in which the MSFN is not available, but it is the only data available at this time. It is expected that when the star-horizon data becomes available, the TEMC accuracy will become worse and corrections to the targeting and minimum L/D requirement may have to be made.

CONCLUSIONS

The minimum L/D for the lunar mission is 0.25. The transearth maneuver should be targeted 0.57° below the zero-lift overshoot boundary to cover the case where the MSFN is unavailable and 0.38°

above the 2500-n. mi. undershoot boundary to cover the case where the RCS is inoperative. Using the targeting criteria, an L/D of 0.25 allows the following flexibilities:

1. It will allow a 1000-n. mi. reentry maneuver capability if the MSFN is available and the G&N system is working.
2. It will provide capture for all cases where the MSFN is available and the maneuvers are executed with the SCS.
3. It will allow capture and a minimum maneuver capability of 500 n. mi. with a 3σ steep flight-path angle, if the MSFN is not available but the service module RCS system is available for midcourse corrections.
4. It will ensure capture if the transearth maneuver is retargeted for the case where the MSFN is not available and the RCS is inoperative. However, it would also result in a $13g$ to $14g$ entry at the 3σ steep flight-path angle.

TABLE I.- GUIDANCE CHANGES

Modification	Reason for change
1. Place LAD and LOD in erasable memory	Allow update of reference L/D
2. $L/D \text{ CMINR} = LAD (\cos 15^\circ)$	Make cross range bias in roll command a function of L/D
3. $KLAT = LAD/24$	Make cross range deadband a function of L/D
4. $Q_2 = 1302 + 1000 \text{ LAD}$	Make final phase range prediction in Hunttest phase a function of L/D
5. $CH1 = 1.0$ $Q19 = 0.4$	Update the range prediction term for the upcontrol phase and make the gravity term more effective in the upcontrol phase
6. Add LEWD iteration logic	Change upcontrol iteration logic from V1 to LEWD. This results in the CM achieving a better start of the upcontrol phase.
7. $GMAX = 8.0$	Correct G-limiter logic to limit the maximum load factor to $10g$

TABLE II.- TRANSEARTH MIDCOURSE CORRECTION ACCURACIES

Case number	Control mode	Propulsion system	Navigation	$3\sigma \Delta Y_{EI}$, deg	Comment
1	G&N	SPS	MSFN	± 0.38	
2	G&N	SPS/RCS	MSFN	± 0.03	
3	G&N	SPS	Onboard	± 1.00	1σ sextant accuracy = 20 arc sec (extrapolated)
4	G&N	SPS/RCS	Onboard	± 0.57	1σ sextant accuracy = 20 arc sec (interpolated)
5	SCS	SPS	Perfect	± 0.50	
6	SCS	SPS/RCS	MSFN	± 0.40	

TABLE III.- MINIMUM L/D REQUIREMENT

Targeting criteria	Failure covered	Total $\Delta\gamma$ required, deg	Minimum L/D to provide 1000-n.mi. entry range control, n.d.
No MSFN - no RCS	None	1.03	0.25
	no RCS	1.38	0.29
	no MSFN	1.57	0.31
	no MSFN - no RCS	2.00	0.35
No MSFN - RCS	None	0.60	0.21
	no RCS	0.95	0.25
	no MSFN	1.14	0.27
	no MSFN - no RCS	--	No capture without retargeting
MSFN - no RCS	None	0.53	0.21
	no RCS	0.88	0.24
	no MSFN	--	No capture without retargeting
	no MSFN - no RCS	--	No capture without retargeting

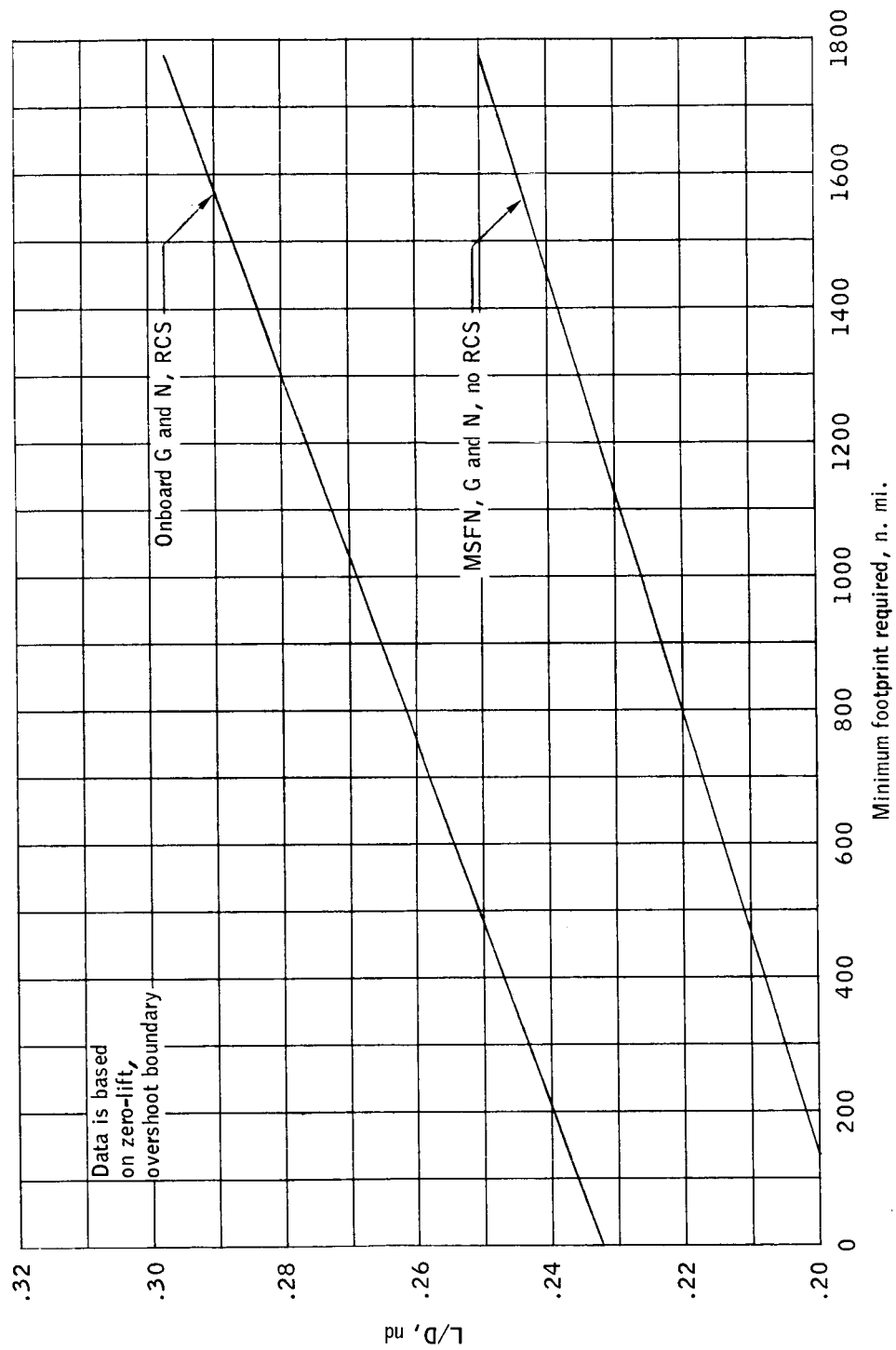


Figure 1.- L/D requirement as a function of maneuver capability.

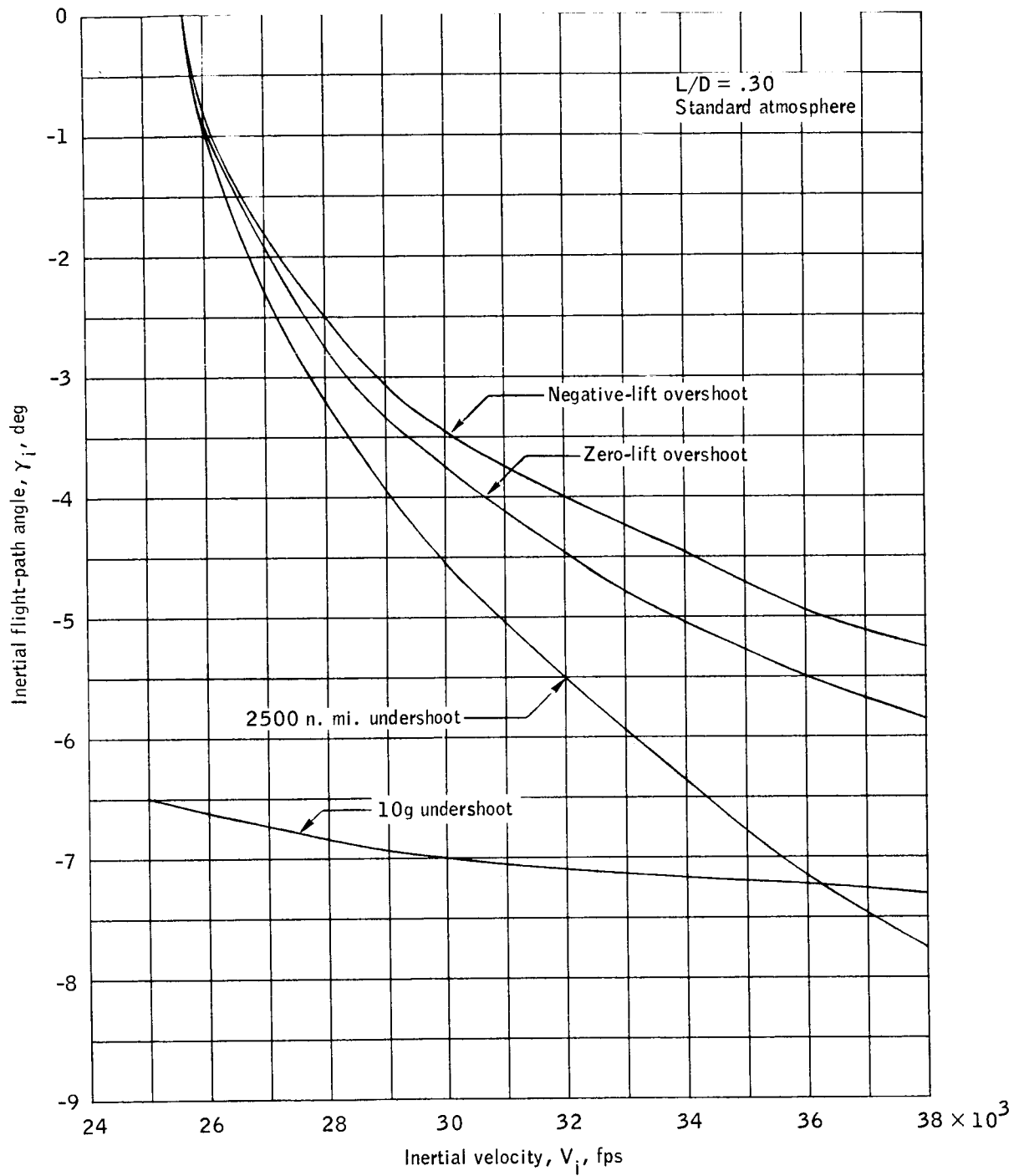


Figure 2.- Entry corridor.

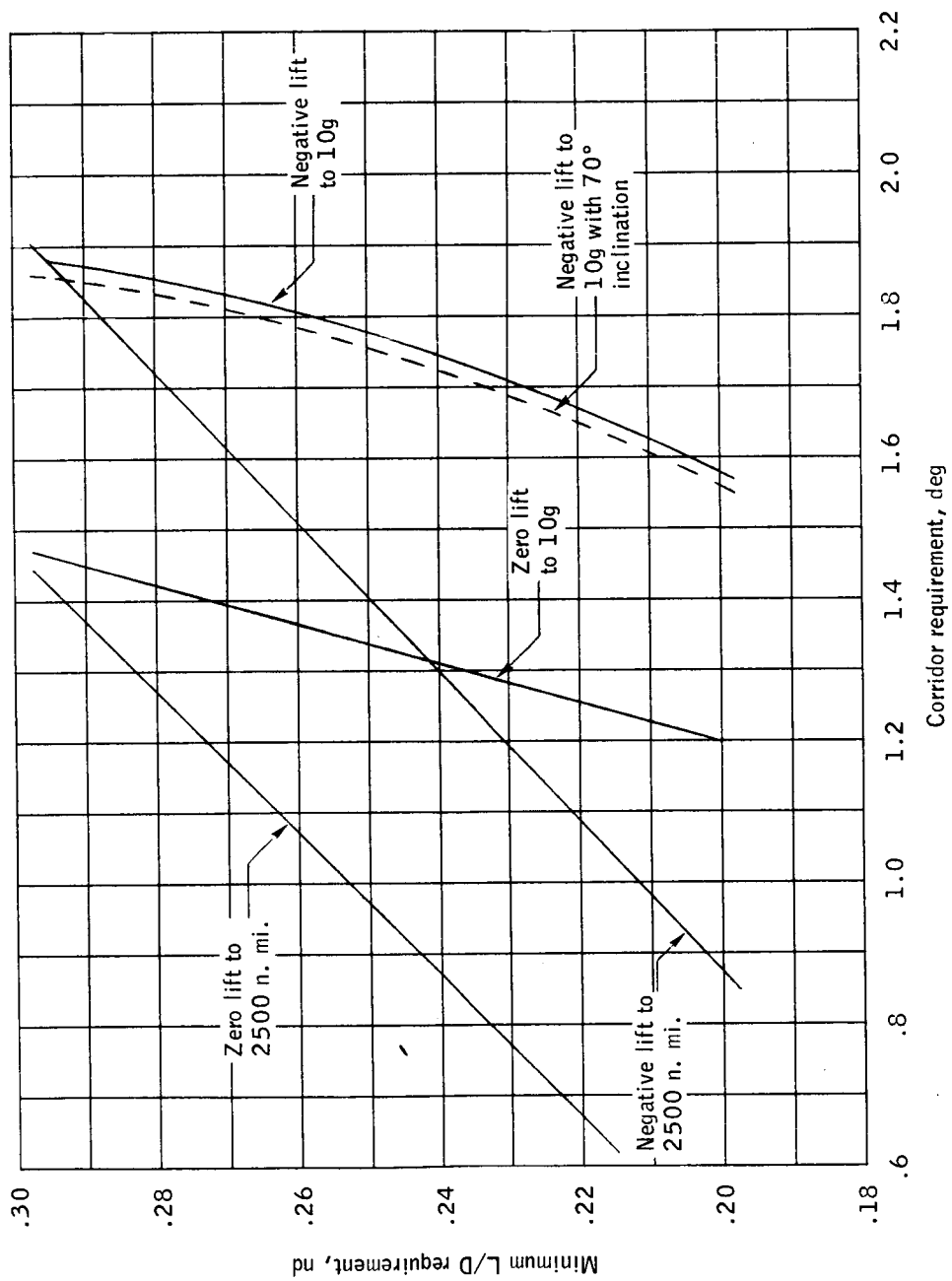


Figure 3.- Minimum L/D required as a function of corridor requirement.

REFERENCES

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2. MIT: Apollo CM Entry Guidance Evaluation for Low Lift-to-Drag Ratios. MIT Document AG-313-67, August 18, 1967.
3. Mayer, John P.: Recommended Changes to the Final Phase Logic of the Reentry Guidance. NASA Memorandum 67-FM53-313, August 18, 1967.